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On the Role of Interaural Level Differences in Low-Frequency Pure-Tone Lateralization

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Summary

While the “Duplex Theory” of sound localization is often interpreted such that low-frequency sounds are localized mainly based on interaural phase differences, and high-frequency sounds based on interaural level differences, some studies have shown an interaction of low-frequency interaural phase and level differences. Using a psychoacoustic lateralization experiment, the present study demonstrates that small interaural level differences are indeed effective in resolving lateralization in the ambiguous range of interaural phase differences at all tested frequencies. These ambiguities occur in free-field conditions at frequencies above about 500 Hz, which is shown by analyzing the magnitude of interaural differences as they occur in typical free-field scenarios. On that basis this study further concludes that naturally occurring interaural level differences on their own are sufficient to correctly attribute sound sources to left or right in many conditions, even at frequencies below 500 Hz.

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1. Introduction

In his influential 1907-paper [6], Lord Rayleigh introduced the basis for what has come to be known as the “Duplex Theory” of sound localization. Essentially, the duplex theory states that low-frequency sounds are localized predominantly based on interaural phase differences, as the shadowing effect of the head only results in small interaural level differences in that frequency range. High-frequency sounds, on the other hand, are mainly localized using interaural level differences, as the impact of the head shadowing effect on interaural level differences increases with frequency. Additionally, interaural phase differences become ambiguous at about 700 Hz, where the stimulus wavelength approximately equals the head circumference. Interestingly, the auditory system is able to detect interaural phase differences past the ambiguity limit up to about 1300 Hz [1], and the sensitivity to interaural level differences at low frequencies was found to be similar to the interaural level difference sensitivity at high frequencies [13]. These findings suggest an interaction between interaural level differences and interaural phase differences in the low-frequency range. The nature of this interaction has been studied extensively [7, 2] and, depending on their sign, interaural level differences were found to facilitate or counteract the lateralization evoked by interaural phase

differences. Due to the small magnitude of naturally occurring low-frequency interaural level differences in free-field conditions, their influence is often neglected. At the same time, additional cues are necessary in order to resolve interaural phase difference ambiguities at sound frequencies above some 700 Hz in free-field conditions – the interaural level difference being a potential and well-suited candidate. To our knowledge, no study has yet systematically investigated the resolving impact of interaural level differences on lateralization, especially of small interaural level differences as they naturally occur in free-field conditions or various natural listening environments. To that end, this study uses a pure-tone lateralization paradigm to investigate the influence of small interaural level differences on the lateralization evoked by interaural phase differences. Aspects of the practical relevance of the results are discussed in the light of typical free-field interaural level differences.

2. Methods

In order to evaluate a potential interaction between interaural level differences and interaural phase differences, we conducted a left-right task experiment [10]. Tone impulses (700 ms, including 160 ms Gaussian onset and offset slopes) were presented dichotically at one-octave spaced frequencies between 125 Hz and 1 kHz, with interaural phase differences introduced by shifting the starting phase of the tone at one ear relative to the other, without changing the stimulus envelope. The sound-pressure level

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(SPL) in the diotic condition at 125 Hz was set to 72 dB SPL, with the headphones calibrated based on their nominal sensitivity at 1 kHz. The levels at all other frequencies were determined based on the equal-loudness contours according to ISO 226:2006 [15], with the aim of approximately balancing loudness across the conditions. interaural level differences were then introduced by amplifying the left and right signals by half the desired interaural level difference, respectively. 21 evenly spaced interaural phase differences between $-\pi$ and π were combined with the interaural level differences 0, ± 0.5 , ± 1 , ± 1.5 , ± 2 , ± 4 , ± 8 dB. At frequencies below 1 kHz, each interaural phase difference was combined with only the interaural level differences with the sign of the interaural phase difference, while at 1 kHz, all interaural phase differences were combined with all interaural level differences. Each stimulus condition was presented and evaluated ten times in random order. The results were collected in four sessions per subject (one session per frequency), each lasting on average 48 min, with a short break after half the stimuli.

Ten unpaid, naïve with respect to the experiment, and inexperienced volunteers (23–41 years, median 27 years, all right handed) with no reported hearing deficits and absolute thresholds within ± 15 dB of ISO 226:2006 [15] took part in the experiment. The subjects were seated in a sound-insulating booth and were presented with the stimuli using the same pair of circumaural headphones (HD 650; Sennheiser electronic GmbH, Wedemark). The specific headphones were selected due to their low inter-individual and intra-individual variability based on [9]. They were interaurally equalized with respect to amplitude and phase [11], so that the relevant sound-pressure time functions measured on a coupler according to IEC 60318-1:2009 [14] were identical within the accuracy of the measurement procedure. The subjects were asked to sit upright, face a specific wall and indicate, by pushing one of two buttons, whether the hearing sensation occurred “left or right”, with no further explanation [10]. Prior to the experiment and after reading the written instructions, a basic understanding of the instructions was verified within a short example experiment. Answers to potential procedural questions were limited to “yes” or “no”, and the example was repeated until the subject felt comfortable with the procedure. No further instructions were provided.

2.1. Analysis of interaural phase differences and interaural level differences

For approximating the typical magnitudes of naturally occurring free-field interaural phase differences and interaural level differences in human listeners, free-field binaural transfer function pairs of 139 subjects from the freely available database of the acoustics research institute [4] were analyzed. The transfer functions were estimated by individually calculating the discrete Fourier transforms of the finite impulse responses corresponding to the left and right ears that reflect the geometric arrangement of interest (variation of the sound-incidence azimuth in the horizontal plane at a fixed source distance of 1.2 m). The in-

teraural phase differences and interaural level differences for each position were estimated by subtracting the corresponding phase and level values of specific single discrete Fourier transform bins. The results are depicted in terms of the arithmetic mean values over the dataset in Figure 1 a. Additionally, Figure 1 b shows the frequency-dependent maximum values over all included source positions. The dashed lines indicate possible descriptive approximations, where interaural phase differences corresponding to 700 μ s delay appear to fit the data frequency-independently well. Consequently, interaural phase differences representing $\pm 700 \mu$ s are taken as an approximation of the range of naturally-occurring free-field interaural phase differences (abbrev.: natural range). Regarding interaural level differences, frequencies below 500 Hz result in maximum interaural level differences around 4.5 dB, while at frequencies of 500 Hz and above, the maximum interaural level difference increases by about 6 dB/octave. As the results depend on measurement setup and transfer function definition, the data are considered an approximation of the actual values.

In order to evaluate whether the supportive effect of interaural level differences is relevant in natural settings, the average magnitudes of interaural level differences and interaural phase differences, as they would occur in a typical free-field setup, were analyzed. The first two columns of Figure 1 a show interindividually averaged interaural phase differences and interaural level differences as functions of azimuth for different stimulus frequencies. For the three lower frequencies, both interaural level difference and interaural phase difference show an approximately sinusoidal dependence on azimuth, with the maximum interaural phase difference below π . At 937.5 Hz, the maximum interaural phase difference is about 1.4π , and interaural phase difference ambiguity is visible, as multiple azimuths correspond to the same interaural phase difference. The third column of Figure 1 a shows interaural level differences plotted against the corresponding interaural phase differences, for each azimuth. This representation visualizes that interaural phase difference ambiguities can be resolved by interaural level differences.

3. Results and Discussion

Figure 2 exemplarily shows the inter-individual medians of the left-right experiment for 500 Hz (left) and 1 kHz (right), represented as the fraction of stimuli rated *on the right*. As found in previous experiments [10], the results for the two frequencies below 500 Hz only showed minor differences to those obtained at 500 Hz so that the results will be discussed based on the two frequencies shown in Figure 2. The columns in this figure represent the frequencies of the tone impulses, the rows indicate selected interaural level difference conditions (label on the right). At 0 interaural phase difference and 0 interaural level difference (horizontal centers, first row), the subject group responded at chance level. With increasing interaural phase difference (at 0 interaural level difference; towards the right), the fraction of hearing sensation reported on the

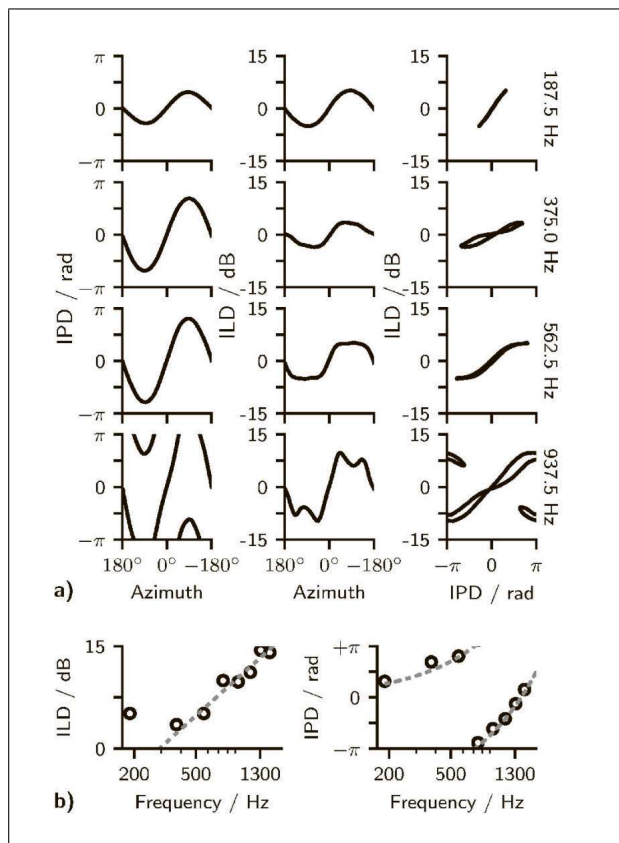


Figure 1. (a) Average horizontal-plane interaural phase differences (first column) and interaural level differences (second column), estimated from 139 binaural impulse response pairs of the acoustics research institute database [4]. The third column shows each interaural level difference plotted against the corresponding interaural phase difference. (b) Maximum estimated horizontal-plane interaural level differences (left) and interaural phase differences (right) as functions of frequency. The dashed contours represent descriptive approximations: line with 6 dB/octave for maximum high-frequency interaural level differences (left) and interaural phase differences corresponding to 700 μs delay for maximum interaural phase differences (right).

right increases, until saturating at 100%. At large interaural phase differences, the fraction of responses to the right starts to decrease again, likely due to an ambiguity introduced by interaural phase difference wrapping. In the 500 Hz condition, the ambiguity effect starts to manifest itself in the data approximately at the limits of the natural range (dashed vertical lines in Figure 2). At 1000 Hz, however, 0.7 ms corresponds to an IPD of approximately 1.4π (abscissa limits in Figure 2), resulting, according to Figure 2, more or less in a left/right reversal of the left-right task results. This appears plausible, as an interaural phase difference of 1.4π is identical to -0.6π . Opposed to the 500 Hz conditions, ambiguity effects occur clearly within the natural range. As the ambiguity effects start to be visible at interaural phase differences at the limits of the natural range at 500 Hz and lie inside this range at 1 kHz, it appears reasonable to assume that ambiguity effects within the natural range become perceptually relevant at frequen-

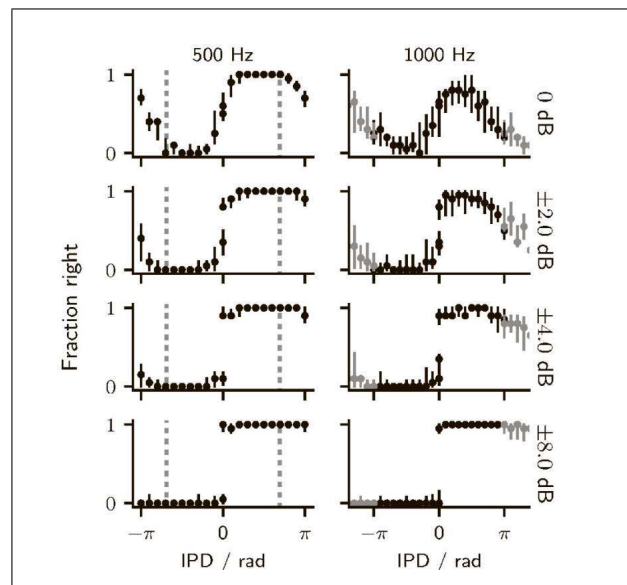


Figure 2. Results of the left-right task experiment for 500 Hz and 1 kHz. Shown are the interindividual medians with 25% and 75% percentiles for all interaural phase differences (abscissae), combined with selected interaural level differences (rows). The vertical dashed lines indicate the interaural phase differences equivalent to $\pm 700 \mu\text{s}$. Duplicate interaural phase differences (i.e. $|\text{IPD}| \geq \pi$) are shown lighter.

cies of 500 Hz and above, with an amount that increases with frequency.

Each row in Figure 2 shows the results for a selected interaural level difference condition. The sign of the added interaural level difference is always identical to the sign of the interaural phase difference (e.g. -2 dB at $-\pi$), so that mostly non-conflicting cues were presented. As expected from literature [2], the addition of those interaural level differences mostly supports the lateralization due to the interaural phase difference (rows 2, 3, and 4 of Figure 2). At 2 dB, this effect is already clearly visible, and 8 dB is sufficient to more or less fully resolve the ambiguity effects with the intermediate interaural level difference values (not shown) following this trend. Analyzing the magnitudes of the interaural level differences calculated from the free-field transfer functions at 937.5 Hz, the maximum interaural level difference was found to be 9.8 dB, which, compared to the experimental data should be sufficient to fully resolve ambiguities.

The data in Figure 2 suggests that small interaural level differences may already influence the left-right task results, at least at certain azimuths that are not affected by interaural level difference-ambiguity effects (e.g. interaural phase differences between approx. $\pm 0.5\pi$ in Figure 2), some combinations of which are naturally relevant interaural phase difference and interaural level difference combinations (compare to data in Figure 1 a). In the experimental paradigm used in this study, the influence of interaural level differences can only be examined where the left-right task results are not saturated due to the interaural phase difference alone.

In order to address the effect of small interaural level differences in more detail, an analysis was conducted for the zero-interaural phase difference condition only. The results for this condition are shown in Figure 3. A two-way analysis of variance (repeated measurement ANOVA) was conducted over the left-right task results with the two factors ILD and frequency. All thirteen interaural level differences and four frequencies were included. The effect of frequency yielded [$F(3, 27) = 1.07$, $p = 0.38$], indicating no significant main effect of the factor frequency. This finding is in agreement with previous studies that report no influence of frequency on the sensitivity to interaural level differences [13]. The factor interaural level difference, on the other hand, shows a highly significant main effect [$F(12, 108) = 83.20$, $p < 0.0001$], with no significant interaction with the factor frequency [$F(36, 324) = 1.11$, $p = 0.32$]. A post-hoc comparison according to Tukey reveals significant ($p < 0.05$) differences to occur first between the zero interaural level difference condition and interaural level differences of ± 1.5 dB, with a non-significant comparable trend for smaller interaural level differences.

The main interest of this study was the impact of small interaural level differences on the lateralization of tone impulses. The experimental results showed that the exclusive use of interaural phase differences results in ambiguity effects at frequencies of 500 Hz and 1 kHz. It was also shown that the addition of small interaural level differences of some 4 dB largely resolved these ambiguities. This finding does not directly support the conclusion that, in the low-frequency range, interaural phase differences dominate interaural level differences [12]. In the 1 kHz, 1.4π condition, the IPD clearly indicates a sound source in the left hemifield. Once an interaural level difference of realistic magnitude is added, this “inversion” is resolved, resulting in a hearing sensation lateralized to the right. This suggests that interaural phase difference and interaural level difference are not separate “cues”, but that hearing sensation properties arise based on most plausible combinations of the information extracted from the stimuli by various neuronal processing stages [8], rather than one arbitrarily-defined (physical) “cue” dominating the other.

4. Summary and Conclusions

In agreement with previous localization studies [3], this study shows that interaural level differences can resolve interaural phase difference ambiguity in lateralization at all studied frequencies, which becomes relevant in free-field settings starting at frequencies as low as 500 Hz, the same frequency as stated in the original publication on the *duplex theory of localization* by Lord Rayleigh [6]. It is important to note that, for natural stimuli such as speech, interaural level differences are not the only mechanism that could resolve ambiguities. In these cases, both low-frequency amplitude modulations and the evaluation across frequencies may also convey unambiguous information.

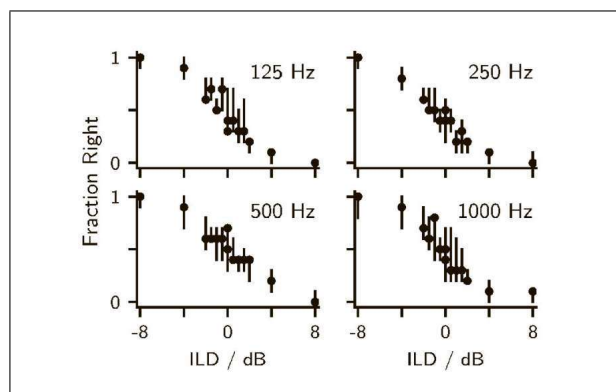


Figure 3. Results from the experiment of Figure 2, depicted as functions of interaural level difference at 0 interaural phase difference.

Using the same experimental data, this study also addresses whether interaural level differences affect the left-right task result in parts of the horizontal plane and at frequencies that are not subject to interaural phase difference ambiguity. At zero interaural phase difference, interaural level differences as low as 1.5 dB cause a significant effect in the data presented here. Interaural level differences of 4 dB were found to be sufficient to reliably attribute the hearing sensation to left or right, even without an interaural phase difference. This finding suggests that two sound sources in opposite hemifields can be attributed correctly based on interaural level differences only, as long as the source positions correspond to interaural level differences larger than ± 1.5 dB. Interaural level differences of this magnitude occur for sources in the horizontal plane at all audible frequencies, even below 500 Hz. The latter conclusion appears relevant to the interpretation of various interaural phase difference-related localization experiments conducted in the free sound field or with virtual-acoustics techniques, as the present study indicates that such experiments may include effects of both interaural phase differences and interaural level differences, even at low frequencies.

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